

## Reduction of Hydraulic Conductivity Due to Microbial Effects

Katsutoshi SEKI\*, Tsuyoshi MIYAZAKI\*\* and Masashi NAKANO\*\*

\* Division of Agriculture and Agricultural Life Science,  
Graduate School of The University of Tokyo

\*\* Faculty of Agriculture, The University of Tokyo

**Abstract** A series of column experiments were carried out to elucidate the effects of microorganisms on reduction in the saturated hydraulic conductivity,  $K_s$ , of paddy field soil.

The  $K_s$  of surface 1 cm layer decreased 2 orders of magnitude during 118 day period of percolation of 50 ppm glucose solution. After the alternation of percolation to germicide ( $\text{NaN}_3$ ),  $K_s$  increased rapidly. Population of bacteria near the surface did not increase, but that of fungi near the surface increased hundred times. Therefore it was proved that the first cause of  $K_s$  reduction is clogging of soil pores by hyphae of fungi and microbial synthesized products.

The second cause of  $K_s$  reduction is occlusion of pore space by gas produced by anaerobic bacteria. The redox potential of all depths was below  $-150 \text{ mV}$  at 15 day, which was sufficiently met for the  $\text{CH}_4$  production. From calculation of production and resolving rate, it was explained that all  $\text{CO}_2$  resolved in percolation, and that  $\text{CH}_4$  did not resolve perfectly. It is estimated that 14% of gas filled pore was occluded by  $\text{CH}_4$  gas and the occlusion contributed to the  $K_s$  reduction.

**Key Words:** Soil-microbial effects, Hydraulic conductivity, Clogging, Methane

### I. INTRODUCTION

It is known that the microbial activity decreases the saturated hydraulic conductivity,  $K_s$ , both directly and indirectly. The first direct effect of microbial activity on the  $K_s$  decrease is the biological clogging of soil pores (Allison, 1947<sup>1)</sup>). Microbial cells and their synthesized products such as glycocalyx (Costerton et al., 1981<sup>2)</sup>) exist on soil surface by forming biofilms (Voice et al., 1992<sup>3)</sup>, Taylor et al., 1990<sup>4),5)</sup>) or by forming microcolony (Harvey et al., 1984<sup>6)</sup>, Moltz et al., 1986<sup>7)</sup>). Rittman (1993)<sup>8)</sup> showed that the formation of microorganisms and their synthesized products is determined by surface loading of substrate.

Gupta and Swartzendruber (1962)<sup>9)</sup> conducted column experiment with quartz sand and observed that the  $K_s$  decreased remarkably when bacterial number exceeded  $4 \times 10^5$  per

gram of sand by the dilute plate counting method. However, the volume of bacterial cells was only 0.00031% of the volume of soil pore, because the dilute plate counting method underestimates number of bacteria and fungi<sup>10)</sup>. Vandevivere and Baveye (1992)<sup>11)</sup> calculated biomass density from the phospholipid content. According to their calculation, the volume of bacterial cells was 2.4%, 4.8%, 8.5%, respectively, of pore volume, when the  $K_s$  decreased tenth, hundredth, thousandth of the initial value.

The second direct effect of microbial activity on the  $K_s$  reduction is the occlusion of pore necks by gas produced through microorganisms (Poulovassilis, 1972<sup>12)</sup>). Reynolds et al. (1992)<sup>13)</sup> showed that the  $K_s$  decrease of peat soil is caused mainly by the occlusion of pore necks by methane gas.

The indirect effect of microbial activity is the improvement of the reduction of soil under submergences, which makes ferrous iron [ $\text{Fe}(\text{II})$ ] resolve in soil solution. Motomura (1969)<sup>14)</sup> showed that the  $K_s$  decreases under

\* 東京大学大学院農学生命科学研究科

\*\* 東京大学農学部

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the condition of the reduction as the solved Fe (II) is so active that it is apt to hydrate or absorb to soil colloid, and results in a decrease of the effective pore space used to water percolation. Miyazaki et al. (1991<sup>15</sup>), 1993<sup>16</sup>) showed that the decrease in the  $K_s$  are more severely observed in paddy field soils than that in upland or forest soils especially at the depth of 20 to 30 cm. They referred to the suggestions made by Mitsuchi (1970)<sup>17</sup> and deduced that such decrease of the  $K_s$  occurred due to the reduction of iron accumulated at a particular layer, 20 to 30 cm, in paddy field.

The objectives of this study are to measure the  $K_s$  changes with time by the prolonged water flow in columns and to show the microbial effects on the  $K_s$  decrease.

## II. Experimental

### 1. Soil

The Soil was sampled in the hard-pan layer, 25 to 33 cm, of paddy field of the University of Tokyo at Tanashi, Tokyo (Kanto loam, Andosols, light clay; clay 35%, silt 15%, sand 50%). The soil was kept at the temperature of 10°C to minimize microbial activity before it was packed with experimental column.

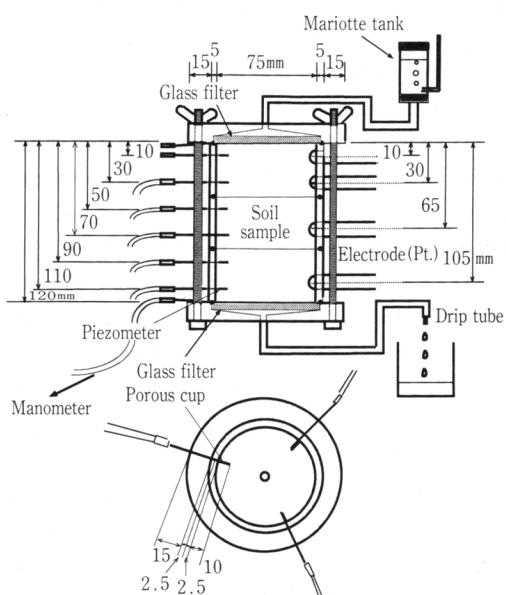


Fig. 1 Schematic diagram of acrylic plastic column

Table 1 Conditions of columns

column	Percolation solution	Bulk density (g/cm <sup>3</sup> )	Percolating period (days)
A	glucose <sup>1)</sup>	0.66	162
B	glucose	0.64	18
C	glucose	0.79	155
D	germicide <sup>2)</sup>	0.67	39

1) 50 ppm glucose

2) 50 ppm sodium azide

### 2. Apparatus

The soil sieved through 2 mm screen was dried to the water content of 78%, and packed uniformly with the acrylic plastic column (Fig. 1). Three piezometers were inserted in the wall of the column at every one of the six different depths, 1 to 11 cm. A three-way valve was connected to each piezometer to sample soil solution for the determination of glucose concentration, and to measure the pressure head using water manometers. At the top and bottom ends of the column, three piezometer tips contact the glass filter. Four electrodes were inserted at different depths to measure the redox potential.

### 3. Experimental Conditions

Four types of column experiments were conducted under saturated condition (Table 1). The solution applied to the first three columns contained glucose of 50 ppm, and that to the last column contained sodium azide ( $\text{NaN}_3$ ) of 50 ppm, which is a strong germicide. Comparison of the results of these two types of solution will make it possible to discuss the biological effects on the changes in hydraulic conductivities. After flowing glucose solution during 118 days, sodium azide was applied to column A as germicide. Because germicide was supplied to the column A, microbial measurement was impossible. Therefore microbial measurement was conducted in column B. In order to discuss the effects of the bulk density, column C was packed in higher bulk density than columns A and B. The soil of the last column was autoclaved (120°C, 1.2 atm, 120 min) before packing with the column.

Applied hydraulic gradient was 10 for column

C and 1 for other columns. Hydraulic gradient of the column C was set higher than other columns because the initial saturated hydraulic conductivity was very small and accordingly the flux was too small. The hydraulic gradient of column A flowing glucose was altered to 2 after 14 day. All columns were covered with black sheet to keep dark and were set in a room of  $30 \pm 1^\circ\text{C}$ .

#### 4. Procedures and Measurement

After all columns were saturated with distilled water from the bottom end of the column, water containing substrate or germicide was applied on the soil surface out of a Mariotte tank. Profiles of pore water heads in the column were measured every day with manometers. Average values of three piezometers installed at the same height were used for calculation of the saturated hydraulic conductivity,  $K_s$ . The saturated hydraulic conductivity in different layers of the column was calculated from flux and pore water head by using Darcy's equation. Flux was measured by the discharge rate of effluent from the drip tube. Glucose concentration of pore water was measured by the hexokinase glucose-6-phosphate-dehydrogenase method to estimate the microbial consumption of substrate at each depth.

After every run, all columns were sliced, bulk density was measured gravimetrically and numbers of microorganisms were measured by the dilute plate counting method. Egg albumin agar culture was used for the bacterial counting and rose bengal agar culture was used for the fungal counting.

### III. RESULTS

#### 1. Hydraulic conductivity change

When germicide was supplied, the saturated hydraulic conductivity,  $K_s$ , took somewhat different values at different layers, but the change in  $K_s$  with time was very small in each layer (Fig. 2). The small  $K_s$  value at the top 1 cm of the soil is probably due to the clogging of soil pores with suspensions in water and excessive compression through packing procedure.

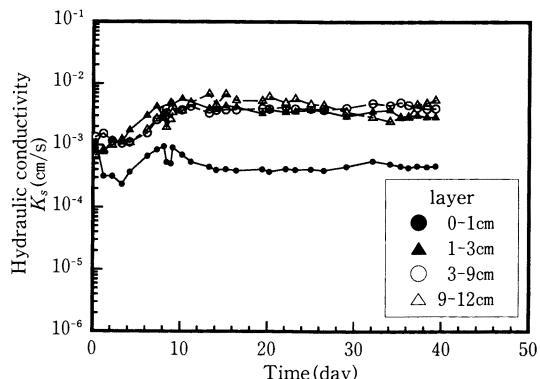


Fig. 2 Changes in  $K_s$  of each layer with time (germicide)

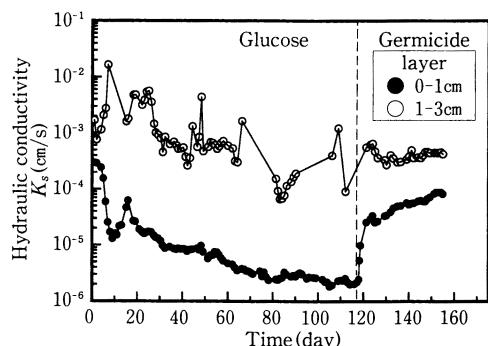


Fig. 3 Changes in  $K_s$  of each layer with time (Column A, glucose)

When glucose was used as the percolating solution, remarkable change in  $K_s$  was observed in the top 1 cm layer (Fig. 3). It was difficult to calculate  $K_s$  at the depth below 3 cm because head differences were too small.

Hydraulic conductivity in the top 1 cm layer decreased remarkably during first 10 days, increased for 6 days, and decreased again until 118 day. After 118 day, the  $K_s$  decreased two orders of magnitude from the initial value. Hydraulic conductivity increased rapidly when water supply was altered from glucose solution to germicide at 118 day. The  $K_s$  decrease in the layer of 1 to 3 cm was much smaller than that in the layer of 0 to 1 cm.

Hydraulic conductivity of the upper filter decreased remarkably as shown in Fig. 4. It seems that in the upper filter red object was formed by which the clogging of the mesh

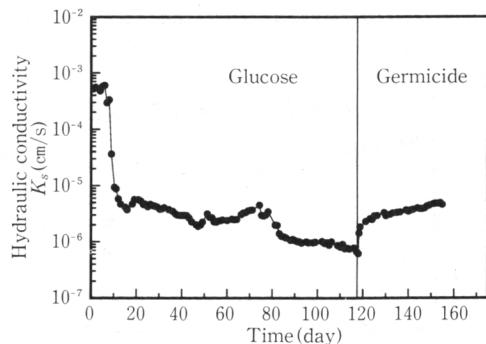


Fig. 4 Change in  $K_s$  of upper filter with time  
(Column A, glucose)

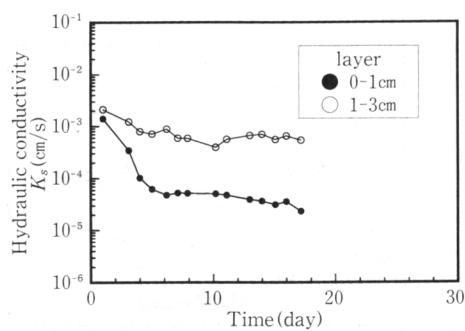


Fig. 5 Changes in  $K_s$  of each layer with time  
(Column B, glucose)

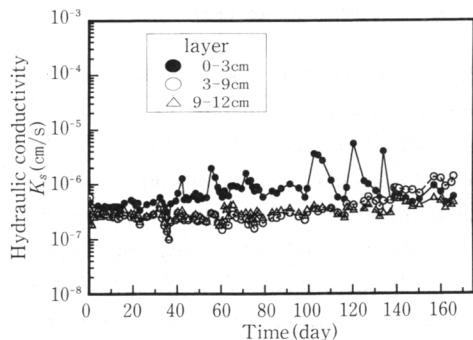


Fig. 6 Change in  $K_s$  of each layer with time  
(Column C, glucose)

occurred and the  $K_s$  decreased.

Hydraulic conductivity of the top 1 cm-layer of column B flowing glucose also decreased rapidly (Fig. 5). However, hydraulic conductivity of each layer of column C flowing glucose did not change during the 162 day period of percolation (Fig. 6).

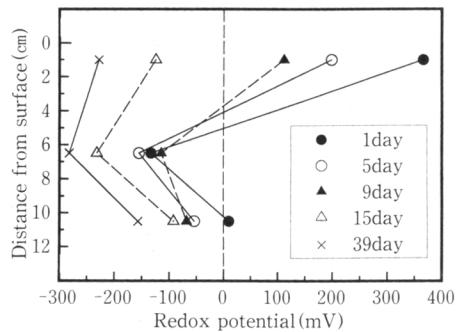


Fig. 7 Change in the redox potential profile with time  
(Column A, glucose)

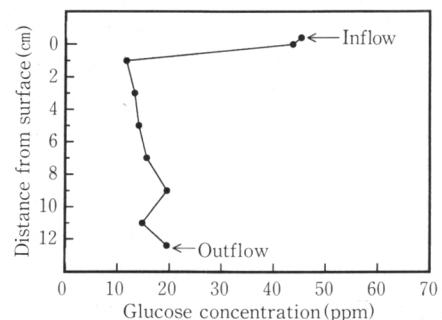


Fig. 8 Profile of glucose concentration in pore water  
(Column A, Glucose, 11 day)

## 2. Redox potential

When glucose was supplied, redox potential of all depths decreased gradually with microbial activity (Fig. 7). After 15 days, the whole column had negative redox potential. However, it was observed that when germicide was used as percolation solution redox potential at the depth of 3 cm fluctuated in the range between 300 mV and 400 mV throughout 39 day flow period.

## 3. Glucose concentration

Glucose concentration of pore water at 11 day of column A flowing glucose is shown in Fig. 8. Glucose concentration decreased from 45 ppm at the 0 cm depth to 12 ppm at the 1 cm depth. Glucose concentration did not change in the layer below the 1 cm depth. This means that most of glucose was consumed by microorganisms within the top layer, 1 cm thick.

## 4. Microbial population

Numbers of bacteria and fungi in the soil of

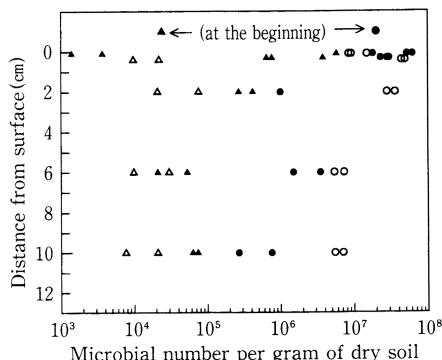


Fig. 9 Numbers of bacteria and fungi. Circle ( $\circ$ ,  $\bullet$ ) is bacteria, Triangle ( $\Delta$ ,  $\blacktriangle$ ) is fungi; Closed is column B, open is column C

columns B and C flowing glucose are shown in Fig. 9. Actinomycete was not detected because the soil was saturated. Numbers of bacteria and fungi plotted as "at the beginning" in Fig. 9 were counted under the submerged condition.

In case of column B of glucose, bacterial number near the upper filter was almost the same as bacterial number at the beginning, while bacterial numbers in the layer below the depth of 2 cm decreased one tenth or one hundredth from the initial value. This is because most oxygen was consumed at the soil surface and lower part of the column became anaerobic, and resulted in decrease of aerobic bacteria.

Fungal numbers of the lower part of the column did not change, while fungal number of the soil surface increased ten to hundred times. Then it seems that the  $K_s$  decrease was accompanied by the population growth of fungi.

Numbers of bacteria and fungi in the column C flowing glucose did not change at all depths during the flow period.

#### IV. DISCUSSION

##### 1. Biological clogging of soil pores

The dilute plate counting method tends to underestimate the microbial number, and hence the calculation of volume of microbial cells using the data of Fig. 9 is not adequate. However, the relative change of microorgan-

isms can be evaluated in Fig. 9. From the fact that number of fungi of column B increased hundred times at the surface, it is supposed that clogging of fungal hyphae at the surface caused the  $K_s$  decrease. The flowing period of column B was 18 days. Therefore,  $K_s$  decrease due to the fungal clogging may have occurred mainly in the first 18 days.

##### 2. Occlusion of pores by gas production

(1) Conservation of carbon atom As shown in Fig. 8, most of glucose was consumed at the surface 1 cm layer. It was supposed that a part of the consumed glucose accumulated as solid such as microbial cells and their synthesized products, and the rest was decomposed into gas such as carbon dioxide or methane. In the column A, the amount of glucose solution percolated during the first 118 days period was 40 liters, and solution of 40 liters contains 2 gram of glucose, or 0.8 gram of carbon atom. If the whole consumed glucose is assumed to be accumulated in the soil pores as solid matter, the mass of their carbon atom is equivalent to 3 percent of the soil mass of surface 1 cm of the column. Considering that glucose in solution was partly decomposed to carbon dioxide or methane gas, the mass of solid matter was less than 3 percent of the soil mass. Therefore, it is reasonable to suppose that the biological clogging of soil pores was not the only cause of the  $K_s$  reduction, and that the occlusion of pores by gas produced by microorganisms also caused the  $K_s$  reduction.

(2) Production of carbon dioxide One of gas that can be produced from carbon source in percolation is carbon dioxide. A liter of the percolation solution contains 50 mg of glucose. Supposing that the whole glucose changes to carbon dioxide, the amount of  $\text{CO}_2$  produced becomes;

$$6 \times \frac{50 \text{ mg}}{180} = 1.67 \text{ mmol} \dots\dots\dots(1)$$

Carbon dioxide resolves 39.3 mmol at 20°C, and 23.7 mmol at 40°C, respectively, in 1 L of water under 1 atm. If we use average value of 31.5 mmol at 30°C, the rate of production of  $\text{CO}_2$  in

this case is equivalent to 5% of resolving rate. Therefore, all produced CO<sub>2</sub> should have resolved in solution, and it is unfavorable to consider that the CO<sub>2</sub> generation caused the K<sub>s</sub> reduction.

**(3) Production of methane gas** Methane production occurs when the redox potential is below -150 mV (Wang et al., 1993<sup>18</sup>). In this study, this requirement was satisfied as shown in Fig. 7. Glucose was the only carbon source in the supplied solution, so the following reactions are thought to be the main process of methane production.

At first, carbon dioxide was produced by aerobic respiration. After oxygen of the percolation solution decreased and anaerobic reaction became predominant, fermentation proceeded anaerobically and carbon dioxide, formic acid, acetic acid, and hydrogen were produced. Then methane was produced by carbon dioxide, formic acid, and acetic acid as carbon source and hydrogen gas as hydrogen source. Assuming that whole hydrogen atom in glucose changes to methane, the following reaction proceeded as a whole under anaerobic condition ;



Therefore 1 mol of glucose changed to 3 mol of methane. As one liter of solution contains 50 mg of glucose, the volume of methane produced from 1 L of solution is ;

$$3 \times \frac{50 \text{ mg}}{180} = 0.83 \text{ mmol} \quad \dots \quad (2)$$

This amount is equivalent to 66% of the methane resolving capacity of 1 L of solution under 1 atm. Before percolation, the percolation solution was in equilibrium with ambient air, in which the partial pressure of nitrogen is 0.80 atm. If all of the produced methane resolved in the solution, it should be in equilibrium with methane gas of 0.66 atm, although actually it was not in equilibrium with gas phase. Summing up the partial pressures of nitrogen and methane, the resolving gas should be in equilibrium with gas of 1.46 atm. It means that under the pressure of 1 atm, some part of the methane produced may not have

resolved in the solution and it may have been accumulated in the pore spaces as bubbles. After the equilibrium between the bubbles and the solution was reached, the bubbles should contain nitrogen. However, taking into account that the composition of the bubbles was not measured and that it does not severely affect the following discussion, it was assumed that only the methane gas was in the bubbles.

**(4) Estimation of the amount of methane occluding pore spaces** We assume that after the alternation of percolation to germicide at 118 day, all the methane occluding the pore during the first 118 days period resolved in the solution. After 118 days, the K<sub>s</sub> recovered rapidly for 10 hours, and 0.2 L of solution percolated during this period. Under 30°C and 1 atm, the volume of methane solvable in 0.2 L of solution is

$$0.2 \text{ L} \times 1.27 \text{ mmol L}^{-1} \times 22.4 \text{ cm}^3 \text{ mmol}^{-1} \\ \times \frac{303 \text{ K}}{273 \text{ K}} = 6.3 \text{ cm}^3 \quad \dots \quad (3)$$

From the assumption we have made, this amount is equivalent to the amount of methane occluding pore spaces during glucose percolation period. If we suppose that methane gas existed uniformly in the surface 1 cm layer, 6.3 cm<sup>3</sup> is equivalent to 14% of the gas filled pore. This amount is enough for decreasing K<sub>s</sub> by reducing the effective pore space.

### 3. Other factors that reduce the K<sub>s</sub>

It has been pointed out that the structural changes resulting with swelling and dispersion cause K<sub>s</sub> reduction (Allison, 1947<sup>19</sup>), but it was supposed in this study that it was not the main cause of K<sub>s</sub> reduction, as the changes in K<sub>s</sub> with time were small in the case of germicide percolation experiment.

Formation of Fe (II) is also said to be the cause of the K<sub>s</sub> reduction. In this experiment, it was observed that some kind of metal resolved in solution and accumulated in drip tube of all the columns. Though possibility of Fe (II) formation was also evidenced by the measurement of redox potential (Fig. 7), the quantitative relationship between the Fe (II)

formation and the  $K_s$  reduction is left in future study.

#### 4. Reason that no $K_s$ change was observed in column C

Hydraulic conductivity in column C having bulk density 0.79 g/cm<sup>3</sup> did not decrease for 162 days. The reason might be explained as follows. As the flux of percolation through column C was smaller than that through column A and B, the rate of substrate supply was small, and as a result, microbial growth was limited and little amount of methane was produced. The amount of glucose supplied during 162 days period was 0.11 g, which is only 5.5% of the amount of glucose, 2 g, supplied during the first 118 days period in column A. Another explanation is that because of high bulk density of column C, there was not enough pore space for microbial growth. Porosity of column A was 74% and that of column C was 69%. Little fungal growth in the surface layer of column C was observed as shown in Fig. 9.

### V. CONCLUSIONS

When glucose solution of 50 ppm is applied continuously for 118 days to soil sampled from hard-pan layer of paddy field, hydraulic conductivity of the surface 1 cm layer decreases 2 orders of magnitude.

The first cause of the  $K_s$  decrease is estimated to be the clogging of soil pores by fungi, which grows hundred times, and by microbial synthesized products. The second cause of the  $K_s$  decrease is supposed to be the occlusion of pore spaces by methane gas produced by bacteria. From the conservation of carbon atom and the calculation of gas production and the resolving rate, it was analyzed that in this column experiment all of carbon dioxide resolved in solution, and methane gas occluded pore spaces as much as 14% of gas phase.

In future, further study is required for determining the volume and the composition of gas phase in order to prove that methane gas was produced by bacteria and occludes part of the pore space. It is also left for further study to

elucidate the quantitative relationship between Fe(II) formation and  $K_s$  reduction.

### ACKNOWLEDGMENTS

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[Questions on this paper will be accepted for public debate before Aug 24, 1996.]

## 〔研究論文〕

### 重力式コンクリートダムに作用する 地震時動水圧の2次元解析 —貯水池形状と振動方向の影響—

松本 伸介・長谷川高士・篠 和夫

貯水池形状を規定する幾何学的パラメータと、振動方向が地震時動水圧に与える影響について検討する目的で、2次元境界要素法によりパラメトリックスタディを実施した。その結果、以下に示すように見が得られた。

1) 水平振動の場合、フィレットの勾配が暖やかなほど、取付け高が高いほど動水圧は低下する。

2) 水平振動の場合、池底がフラットに近いほど動水圧は高くなる。

3) 斜方からの突き上げ振動の場合には、水平振動の場合の2倍以上の高い動水圧が発生するケースがある。

4) 前述の各因子が動水圧に与える影響の傾向は、いずれも堤体上面や池底面と振動方向とのなす角度に大きく依存する。

キーワード　重力式コンクリートダム、動水圧(ダム)、数値実験、境界要素法、2次元解析

(農土論集 181, pp. 115~121)

## 〔研究論文〕

### 周面摩擦を考慮した自重圧密

高山 昌照・東 孝寛・肥山 浩樹・新川 豊

スラリー状粘土の圧密特性は、遠心力を利用した自重圧密や浸透圧を利用した圧密実験から決定されている。ここでは、透明なシリンドルを利用した自重圧密実験から圧密解析に必要な土質定数の決定法について述べている。透水係数( $k$ )は自重圧密の初期沈下速度から決定する三笠と高田の方法によるものである。 $k-f$ (体積比)関係は初期 $f$ の異なる自重圧密実験から決定する。 $f-k$ (圧密圧力)関係は、層厚の異なるいくつかの自重圧密実験の実測沈下量と推定値との差を最小にする方法によって決定する。試料高さとシリンドル径の比が大きくなる自重圧密の場合、 $f-k$ 関係の決定には周面摩擦を考慮する必要がある。

キーワード　自重圧密、透水係数、体積比-圧密圧力関係、周面摩擦

(農土論集 181, pp. 131~136)

## 〔研究報文〕

### 灌漑用水に流入したクロボクの除去対策の検討

凌 祥之・安養寺久男

クロボクは、わが国の畠地では最も代表的な土壌であるが、粒子が軽いために、表面流出して灌漑用水に流入することが懸念される。ここでは、非アロフェン質のクロボクが灌漑用水に流入した場合の除去対策を検討するために、予備的な試験を行い、その効果を把握した。その結果、流出するクロボク土量を減少させるためには、土壤を乾燥させることができた。土壤が乾燥すると、耐水性団粒が粗粒化し、輸送抵抗が高まり、水中では沈降を促進させた。汚濁した灌漑用水を滞留させる組織を設ければ、汚濁を軽減することが可能である。その他、フィルターやろ過材を用いて除去する方法を検討したが、問題点も多かった。

キーワード　灌漑用水、汚濁軽減、クロボク

(農土論集 181, pp. 145~151)

## 〔研究論文〕

### 一定流量を取水するために必要な貯水池容量の性質 —ダム利水容量による河川流量時系列の評価(I)—

袁 新・佐藤 政良

水利事業計画の観点から、計画必要貯水池容量を用いた河川流量時系列の評価を行ったため、各水年の必要貯水池容量が互いに独立である限界の最大水利用レベルを検討した。人為的な影響の少ない自然な流量を対象とするため、日本全国から10カ所の多目的ダムを選定し、その流量記録から、河川から一定量を利用する場合について、利用レベルの上昇と必要容量の増加の関係について検討した。この限界レベルは、長期平均流量の40~85%の間にあり、ほぼ最小年流量で決まるが、年流量のつながり方にも影響される。また、必要貯水池容量が開発流量の二次関数で表される範囲をはずれ、急増するのは経年補給への移行によるものであることが明らかになった。

キーワード　貯水池容量、河川流量、時系列、利用水量、水資源開発

(農土論集 181, pp. 123~130)

## 〔研究論文〕

### Reduction of Hydraulic Conductivity due to Microbial Effects (本文=英文)

閔 勝寿・宮崎 育・中野 政詩

土に長期的に栄養水が侵入すると、土の間隙中の土壤微生物と微生物がつくり出す代謝生成物が水の通り道を塞ぐ現象、いわゆる clogging(目詰まり)現象が生じ、土の透水性が低下することが知られている。そこで、栄養水飽和浸透条件下での透水係数の長期変動を調べ、深さ0~1cmの層において、118日間でほぼ2オーダー透水係数が低下することを示した。

透水係数低下の第一の原因是、糸状菌の長い菌糸と微生物の代謝生成物による間隙の閉塞であり、第二の原因是、グルコースから発生したメタンガスが118日間に表層に最大14%の気相率相当量が溶解せず気泡となって間隙中に閉塞されたことによるものであると説明された。

キーワード　土壤微生物の作用、透水係数、目詰まり現象、メタン

(農土論集 181, pp. 137~144)

## 〔研究報文〕

### 奥入瀬川風致保全放流量の評価に関する研究

大久保 博

十和田湖・奥入瀬川の河水統制計画で決められた奥入瀬渓流の風致保全のための放流量の決定根拠について、過去の文献から考察した。その結果、風致のための放流量は奥入瀬渓流直下流の水田に対する用水であることが推察された。また、発電水利との関係についてふれた。さらに子の口(湖口)の制水門が建設される前の自然流況での流量を、昭和44年から昭和56年までのデータを用いて再現し、昼間の放流量は平年の平均流量に相当することを確認したが、自然流況を知る人のイメージとは異なっていた(聴取)。その原因を探るため、風致保全放流量に対するポジティブランゲンスを求めて検討し、保全された景観は秋期の景観であることを考察した。

キーワード　河水統制計画、水利開発、景観、放流量、十和田湖、奥入瀬渓流、風致保全

(農土論集 181, pp. 153~160)